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Image Information Based Configuration Control of Redundant Manipulator in Bilateral System

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Abstract: The paper proposes a construction method of bilateral system using redundant manipulator. In bilateral system, it is important that operation can be realized in narrow space and at remote plate. Then the master-slave robots with redundancy are convenient and needed to achieve the bilateral motion effectively. However, human operation will become difficult because of the multifunctional mechanism. Especially, operating the posture of redundant manipulator by human hand is so difficult because the manipulator redundancy enables to achieve infinite number of the manipulator posture. This paper focuses on a construction of bilateral system so that it assists the human operation by adjusting a configuration control of redundant manipulator. In particular, bilateral system utilizes visual information by cameras to recognize the target object of remote environment in slave. By using this camera information, the assist for the slave operation of redundant manipulator is realized without deteriorating the bilateral motion.

1. INTRODUCTION

Recent researches on robot control including contact motion with the environment are considered extensively. For example, robot arms are substituted for human arms to realize grasping motion, and hence have many potential applications in industry and welfare fields. The bilateral control also enables human operators to feel reaction force from remote environment. This technique has been applied for medical care, stricken areas and so on.

There are a lot of researches concerning grasping manipulation in last several decades. Mishra *et al.*[1] had studied deciding the position and the force of grasping an object, David [2] distinguished between two types of grasp stability. In recent years, the controls of grasping robot which can grasp like human arm have been realized. On the other, the system which interactively communicates position and force parameters between the master and the slave is used generally in bilateral control. Lawrence [3] defined transparency and robust stability for indicating the quality of communication.

There are many studies relating to grasping control or bilateral control besides the above. Although the technique that combines both the controls has many potential application, there are few control methods in that combined system. The redundancy is also needed for further potential applications. For example, it is possible to avoid the obstacle and to carry out the various works in the bilateral system with the redundancy. These technique enable to construct the much versatile systems [4].

However, it isn't easy to operate the redundant robots with human in bilateral system. If a redundant manipulator is operated with handing a point, the manipulator can be some postures by its redundancy. This specific quality is useful to avoid the obstacle and so on, however, it is so difficult to operate the redundant system by human. If the posture which extremely suits manipulating is kept, that is to say, if the manipulability measure is kept larger, the operability of the redundant manipulator is improved [5]. As an alternative problem, it is necessary to recognize the environment information of slave in bilateral system. There are many researches which use a camera as a solution. The most of these researches adopt a method so that the operators work with looking at the robots and environment in slave by fixing a camera on absolute coordinate. However, the visual information is not always enough to work. The versatility is needed for the various works like the minute or the difficult. Then, it is expected that a manipulator with camera in the end effecter has every possibility of executing some difficult operations. For example, working against a moving object may be possible using this mechanics. However, it is so difficult to combine visual information with bilateral system which is operated by human. That information can be useful and have some possibility of disturb the human operating. Therefore, this paper proposes a versatile bilateral system which uses the redundant manipulator with a visual feedback in the slave robot. The assistance for human operators is realized with the visual information. That is, it is realized to combine bilateral control with visual feedback control. As a realization of the purpose, this paper describes improving the posture of the redundant manipulator without disturbing human operation by using null space motion of redundant manipulator.

⋆ This work was supported in part by the National Technological Agency. (sponsor and financial support acknowledgment goes here). Paper titles should be written in uppercase and lowercase letters, not all uppercase.

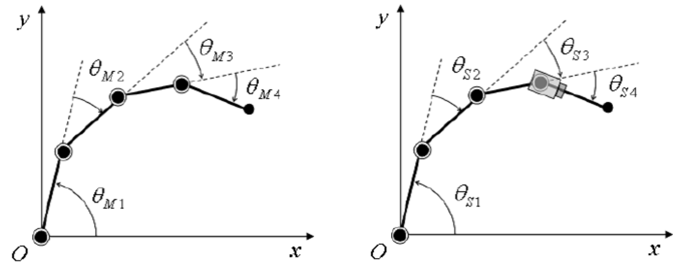

Fig. 1. Model of Redundant Manipulator in bilateral system (left: Master, right: Slave with Camera)

The composition of this paper is described as follows. Section 2 presents modeling of redundant manipulation and camera system. In Section 3, the bilateral system by redundant manipulator is shown. Then the posture control of the redundant manipulator with image information is also shown, and the results of the simulation and experiment are shown in section 4 and 5 respectively. Finally, conclusions are described in section 6.

2. MODELING OF REDUNDANT MANIPULATOR WITH CAMERA SYSTEM

In this section, the kinematic models of a redundant manipulator with camera system is described, and dynamic equations are derived on the basis of the model.

2.1 Redundant Manipulator

The kinematic modeling of manipulator considered in this paper is shown in Fig. 1. Both master and slave manipulators have 4-DOF in $x - y$ plane. In the slave side, PSD(Position Sensitive Detector) camera is mounted on tip position of the manipulator. The velocity relation between tip position vector $\boldsymbol{x}_e^T = (x_e,\ y_e)$ and joint angle vector $\boldsymbol{\theta}^T = (\theta_1,\ \theta_2,\ \theta_3,\ \theta_4)$ is given as follows.

$$\dot{\boldsymbol{x}}_e = \boldsymbol{J}_{aco}^E \dot{\boldsymbol{\theta}} \tag{1}$$

From time differentiation of (1), (2) is obtained.

$$\ddot{\boldsymbol{x}}_e = \boldsymbol{J}_{aco}^E \ddot{\boldsymbol{\theta}} + \dot{\boldsymbol{J}}_{aco}^E \dot{\boldsymbol{\theta}} \tag{2}$$

In the manipulator control, inverse kinematics of (2) as shown in (3) is utilized to obtain joint acceleration reference.

$$\ddot{\boldsymbol{\theta}}^{ref} = {\boldsymbol{J}_{aco}^E}^{+} \ddot{\boldsymbol{x}}_e^{ref} + \left(\boldsymbol{I} - {\boldsymbol{J}_{aco}^E}^{+} \boldsymbol{J}_{aco}^E\right) \ddot{\boldsymbol{\varphi}}_{null}^{ref} \tag{3}$$

Here pseudo-inverse matrix ${\boldsymbol{J}_{aco}^E}^{+}$ is defined as follows.

$${\boldsymbol{J}_{aco}^E}^{+} = {\boldsymbol{J}_{aco}^E}^{T} \left(\boldsymbol{J}_{aco}^E {\boldsymbol{J}_{aco}^E}^{T}\right)^{-1} \tag{4}$$

In the proposed approach, $\ddot{\boldsymbol{x}}_e^{ref}$ is synthesized to realize bilateral control in workspace. $\ddot{\boldsymbol{\varphi}}_{null}^{ref}$ is for improvement of operability of bilateral system.

The dynamics formulation of redundant manipulator is also described as follows.

$$\boldsymbol{\tau} = \boldsymbol{M}\ddot{\boldsymbol{\theta}} + \boldsymbol{h}(\boldsymbol{\theta},\ \dot{\boldsymbol{\theta}}) + \boldsymbol{g}(\boldsymbol{\theta}) \tag{5}$$

$\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{h}(\boldsymbol{\theta},\ \dot{\boldsymbol{\theta}})$ is a term of centrifugal and Coriolis force and $\boldsymbol{g}(\boldsymbol{\theta})$ is a term of gravity. The inertia matrix can be work out by repeating calculating torque of joint using Newton-Euler method.

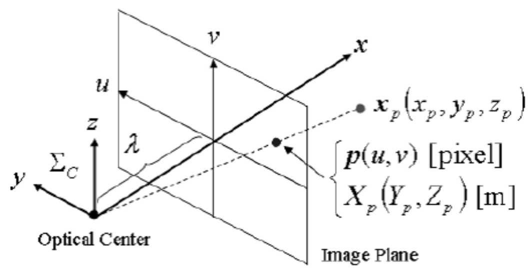

Fig. 2. Perspective Projection

2.2 Camera Kinematics

The kinematic modeling of camera fixed on link4 is shown in Fig. 2. When the external and internal parameters of the camera system are known, position of feature point can be calculated. In Fig. 2, λ is focus length. Equations (6) and (7) show kinematic relation of position vector $\boldsymbol{x}_p = (y_p,\ x_p)^T$ and projection vector ${}^C\boldsymbol{X}_p = \left({}^CY_p,\ {}^CZ_p\right)^T$ in camera coordinate.

$${}^CY_p = \frac{\lambda}{{}^Cx_p} {}^Cy_p \tag{6}$$

$${}^CZ_p = \frac{\lambda}{{}^Cx_p} {}^Cz_p \tag{7}$$

Moreover position vector of pixel point $\boldsymbol{p} = (u,\ v)^T$ and ${}^C\boldsymbol{X}_p$ is given as follows. Here k_u and k_v are scale gains.

$$u = k_u {}^CY_p \ = \ k_u \lambda \frac{{}^Cy_p}{{}^Cx_p} \tag{8}$$

$$v = k_v {}^CZ_p \ = \ k_v \lambda \frac{{}^Cz_p}{{}^Cx_p} \tag{9}$$

To construct visual feedback controller in the latter section, the above equations are utilized.

3. BILATERAL SYSTEM BY REDUNDANT MANIPULATOR

In conventional approaches, control system for bilateral motion is constructed in joint coordinate. In this case, it is difficult to utilize the advanced features of redundant manipulator. To address this issue, this paper proposes bilateral control system based on workspace coordinate.

3.1 4 Channels Bilateral Controller

Fig. 3 shows a general form of 4 channels bilateral controller. The acceleration references in master and slave parts are calculated as follows. Here $\boldsymbol{K}_p$ and $\boldsymbol{K}_v$ are the matrices of position and velocity feedback gains respectively. $\boldsymbol{K}_f$ is a matrix of force feedback gain.

$$\ddot{\boldsymbol{x}}_M^{ref} = \left(\boldsymbol{K}_v + \frac{\boldsymbol{K}_p}{s}\right)(\dot{\boldsymbol{x}}_S - \dot{\boldsymbol{x}}_M) + \boldsymbol{K}_f\,(\boldsymbol{F}_S + \boldsymbol{F}_M) \tag{10}$$

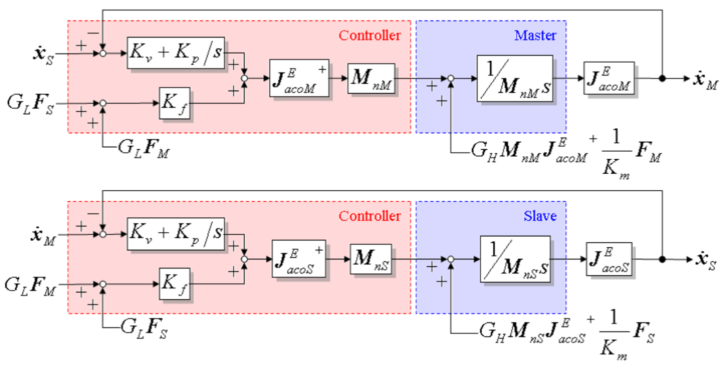

Fig. 3. Bilateral System in Workspace

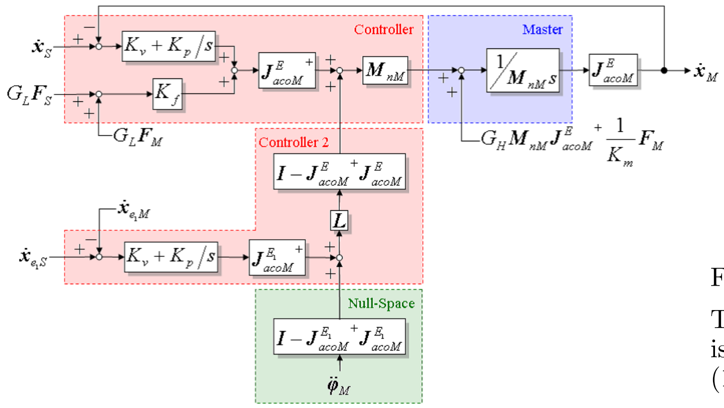

Fig. 4. Bilateral Control of End Effector Joint

$$\ddot{\boldsymbol{x}}_S^{ref} = \left(\boldsymbol{K}_v + \frac{\boldsymbol{K}_p}{s}\right)(\dot{\boldsymbol{x}}_M - \dot{\boldsymbol{x}}_S) + \boldsymbol{K}_f(\boldsymbol{F}_M + \boldsymbol{F}_S) \quad (11)$$

Here it is assumed that $\boldsymbol{F}_M$ and $\boldsymbol{F}_S$ in workspace are applied force in master part and reaction force from environment in slave part respectively. In the proposed approach, each force is calculated from the estimated reaction torque of joint space. The relation between joint torque and workspace force is given by (12) and (13). Here $\boldsymbol{M}_{nM}$ and $\boldsymbol{K}_m$ are equivalent inertia and mass matrices.

$$\boldsymbol{T}_M = \boldsymbol{M}_{nM}\boldsymbol{J}_{acoM}^{E}{}^{+}\boldsymbol{K}_m^{-1}\boldsymbol{F}_M \quad (12)$$

$$\boldsymbol{T}_S = \boldsymbol{M}_{nS}\boldsymbol{J}_{acoS}^{E}{}^{+}\boldsymbol{K}_m^{-1}\boldsymbol{F}_S \quad (13)$$

From (12) and (13), $\boldsymbol{F}_M$ and $\boldsymbol{F}_S$ are calculated from the estimated reaction torque $\boldsymbol{T}_M^{reac}$ and $\boldsymbol{T}_S^{reac}$ by reaction torque estimation observer.

$$\boldsymbol{F}_M^{ref} = K_m\boldsymbol{J}_{acoM}^{E}\boldsymbol{M}_{nM}{}^{-1}\boldsymbol{T}_M^{reac} \quad (14)$$

$$\boldsymbol{F}_S^{ref} = K_m\boldsymbol{J}_{acoS}^{E}\boldsymbol{M}_{nS}{}^{-1}\boldsymbol{T}_S^{reac} \quad (15)$$

3.2 Bilateral Control in Null Space

To improve operability of master-slave motion by human operation, the proposed approach also employs bilateral control in joint of end effector link as shown in Fig. 4. Here $\boldsymbol{K}_p$ and $\boldsymbol{K}_v$ are the same matrices of position and velocity feedback gains in (10). In this bilateral system, end effector configurations of master and slave manipulator operate in sync by the position based bilateral control.

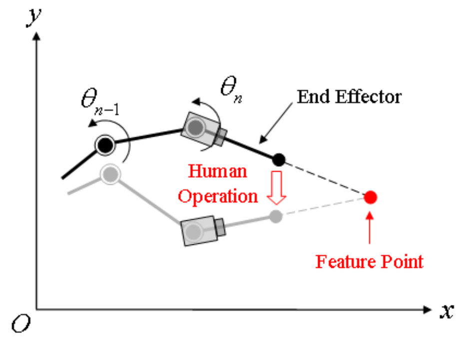

Fig. 5. Configuration Control By Visual Feedback

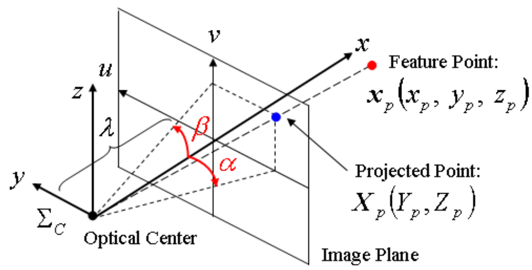

Fig. 6. The Definition of Tracking Angle

This is one of key issues in the proposed strategy. Here $\boldsymbol{L}$ is a selection matrix for null space control and is given by (18).

$$\ddot{\boldsymbol{x}}_{e_1M}^{ref} = \boldsymbol{K}_p\left(\boldsymbol{x}_{e_1S}^{res} - \boldsymbol{x}_{e_1M}^{res}\right) + \boldsymbol{K}_v\left(\dot{\boldsymbol{x}}_{e_1S}^{res} - \dot{\boldsymbol{x}}_{e_1M}^{res}\right) \quad (16)$$

$$\ddot{\boldsymbol{x}}_{e_1S}^{ref} = \boldsymbol{K}_p\left(\boldsymbol{x}_{e_1M}^{res} - \boldsymbol{x}_{e_1S}^{res}\right) + \boldsymbol{K}_v\left(\dot{\boldsymbol{x}}_{e_1M}^{res} - \dot{\boldsymbol{x}}_{e_1S}^{res}\right) \quad (17)$$

$$\boldsymbol{L} = \begin{pmatrix} 1 & & \boldsymbol{0} \\ & \ddots & \\ \boldsymbol{0} & & 1 \\ 0 & \cdots & 0 \end{pmatrix} \quad (18)$$

3.3 Visual Feedback in Null Space

In practical implementation, it is preferable that the configuration of end effector link in slave manipulator faces in the direction of target object that the slave manipulator manipulates as shown in Fig. 5. To achieve this motion, the configuration, that is, the null space motion of slave manipulator is controlled according to PSD camera information. As described before, PSD camera is mounted on the end link of slave manipulator and the visual feedback controller is constructed in the null space of the slave manipulator.

Fig. 6 shows a definition of tracking angle α and β, and each angle is calculated by (6) and (7).

$$\alpha = \tan^{-1}\left(\frac{Y_p}{\lambda}\right) \quad (19)$$

$$\beta = \tan^{-1}\left(\frac{Z_p}{\lambda}\right) \quad (20)$$

Using the above equations, visual feedback controller is constructed as follows. Here K_{Ip} and K_{Iv} are proportional and derivative gains respectively.

$$\ddot{\boldsymbol{\alpha}}^{ref} = K_{Ip}(\boldsymbol{\alpha}_{cmd} - \boldsymbol{\alpha}_{res}) - K_{Iv}\dot{\boldsymbol{\alpha}}_{res} \quad (21)$$

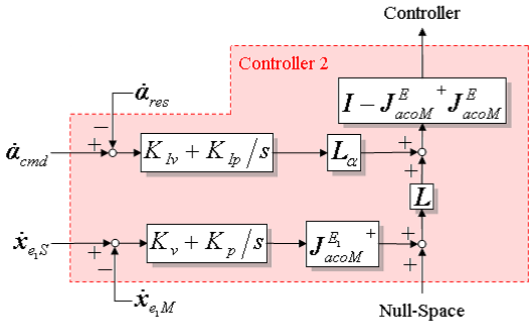

Fig. 7. Bilateral Control Based on Visual Tracking

As described before, slave manipulator is a planer type and β is uncontrollable. Then final acceleration reference for null space motion based on the visual feedback is determined by (22). Here $\boldsymbol{L}_\alpha$ is a selection matrix that makes the control of α effective.

$$\ddot{\boldsymbol{\theta}}_\alpha^{ref} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \ddot{\alpha}^{ref} \\ \ddot{\beta}^{ref} \end{pmatrix} = \boldsymbol{L}_\alpha \ddot{\boldsymbol{\alpha}}^{ref} \tag{22}$$

3.4 Operability Improvement in Null Space

To improve the operability of master-slave system, additional input for null space motion is generated. Then this paper introduces manipulability measure given by (23)[5].

$$\epsilon(\boldsymbol{\theta}_{e_1}) = \sqrt{det\left(\boldsymbol{J}^{E_1}_{aco}\boldsymbol{J}^{E_1}_{aco}{}^{T}\right)} \tag{23}$$

The larger (23), the more the operability increases[5]. In the formulation given by (3), final configuration of redundant manipulator is determined so that (23) becomes large. So, to maximize (23), the minus sign is added to (23) and the input function to null space controller is determined as follows.

$$g_m(\boldsymbol{\theta}_{e_1 M}) \triangleq -\epsilon(\boldsymbol{\theta}_{e_1 M}) \tag{24}$$

Using (24), final acceleration reference for null space motion is given as follows.

$$\ddot{\boldsymbol{\varphi}}_{nullM} = -K^M_{np}\frac{\partial g_m(\boldsymbol{\theta}_{e_1 M})}{\partial \boldsymbol{\theta}_{e_1 M}} - K^M_{nv}\dot{\boldsymbol{\theta}}_{e_1 M} \tag{25}$$

4. SIMULATION

To verify the validity of the proposed approach, simulation is implemented. Figs. 8 and 9 are whole block diagrams of master and slave controller respectively. The controller gains are summarized in Table. 1. Figs. 10 ∼ 13 show simulation results. The controller gains are summarized in Table. 1. Figs. 10 and 11 show configuration response of redundant manipulator. Figs. 12 and 13 are tracking angle error and master force applied by human. From these results, it is found that bilateral control by redundant manipulator is achieved. In particular, small error of the tracking angle is accomplished and the constraint of slave manipulator by visual feedback is effectively realized without deteriorating the bilateral control.

Table 1. Controller Gains and Parameters

Controller Gains		
Bilateral Controller	K_p, K_v, K_f	200, 28, 0.5
Null Space Controller	K_{npM}, K_{nvM}	20, 2
	K_{npS}, K_{nvS}	20, 2
Visual Controller	K_{Ip}, K_{Iv}	25, 10
Initial Values and Parameters		
Initial Configuration	$\boldsymbol{\theta}_{st}$ [rad]	($\pi/2$, $-\pi/2$, $-\pi/2$, $\pi/6$)
Position of Feature Point	${}^{W}\boldsymbol{x}_p$ [m]	(0.323, −0.275, 0.35)

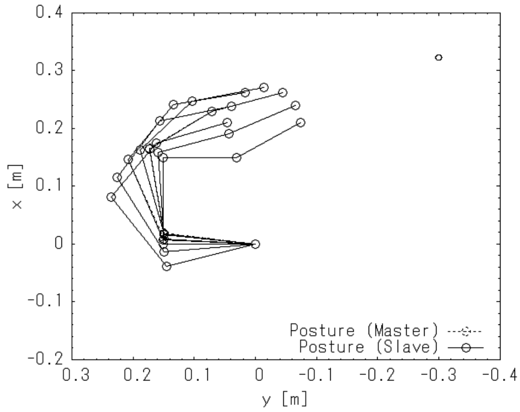

Fig. 10. Configuration Response ($0 < t < 2.5$)

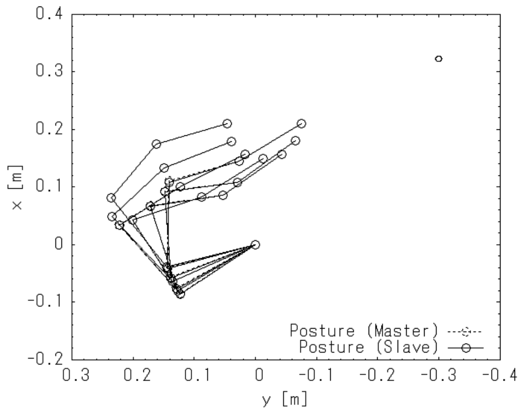

Fig. 11. Configuration Response ($2.5 < t < 5$)

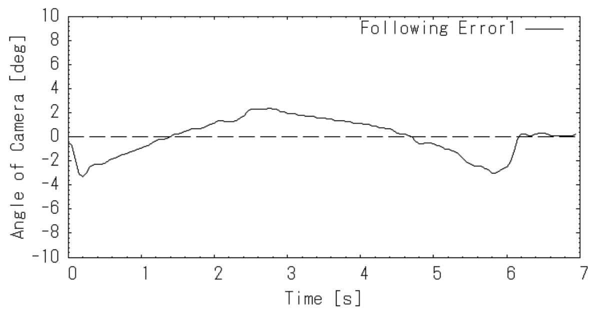

Fig. 12. Tracking Error Angle α

5. EXPERIMENTS

To verify the validity of the proposed approach, several experiments are implemented. Fig. 14 shows an experimental setup. As shown in this figure, PSD camera is mounted on the end effector of slave manipulator.

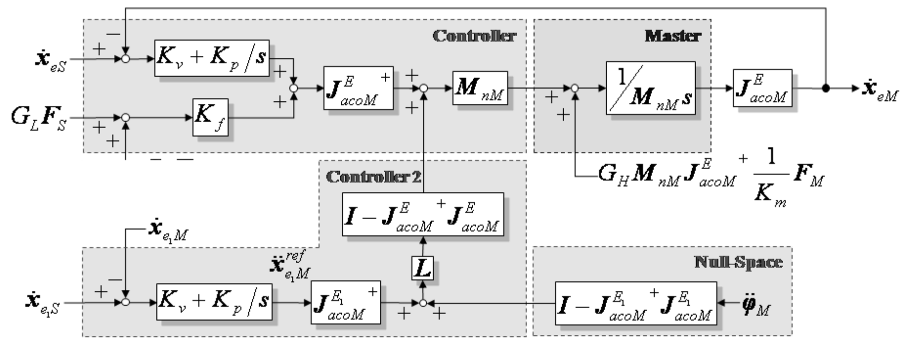

Fig. 8. Block Diagram of Whole Controller in Master Manipulator

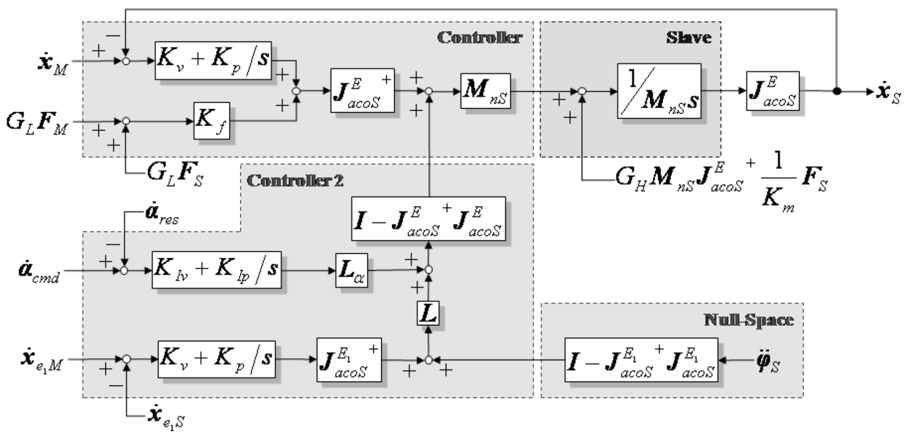

Fig. 9. Block Diagram of Whole Controller in Slave Manipulator

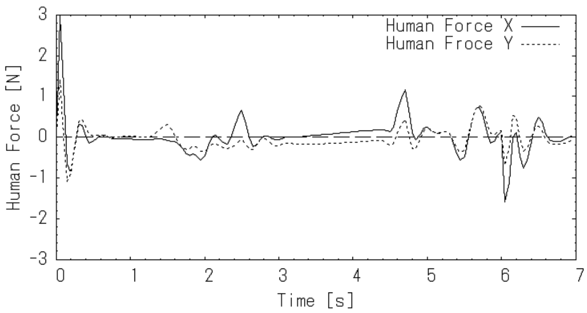

Fig. 13. Estimated Human Force

5.1 *Bilateral Control with Visual Tracking*

Figs. 15 ∼ 18 show experimental results. The controller gains are the same of simulation as shown in Table. 1. Figs. 15 and 16 show configuration response of redundant manipulator. Figs. 17 and 18 are tracking angle error and master force applied by human. From these results, it is found that bilateral control by redundant manipulator is achieved without unknown dynamical effects of redundant manipulator. In particular, small error of the tracking angle is accomplished and the constraint of slave manipulator by visual feedback is effectively realized without deteriorating the bilateral control.

5.2 *Transparency of Bilateral Control*

To evaluate the transparency of bilateral control, effective load is imposed on slave manipulator. The weight of load is 8Kg. The experimental results are shown in Figs. 19 and 20. From these results, it is found that the position and the force responses of slave manipulator well coincide with that of master manipulator, and the transparency of bilateral control is guaranteed.

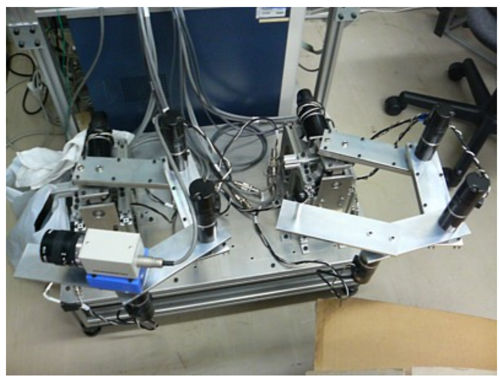

Fig. 14. Experimental System

6. CONCLUSIONS

This paper proposes a method of controlling the posture of the redundant manipulator using the visual information in the bilateral system. In the proposed approach, the combination control of workspace and null space is employed for bilateral control, and this makes it plausible to introduce the additional posture control by null space motion effectively. In the master part, the manipulability of redundant manipulator is utilized to improve the operability of master manipulator. On the other hand, in slave

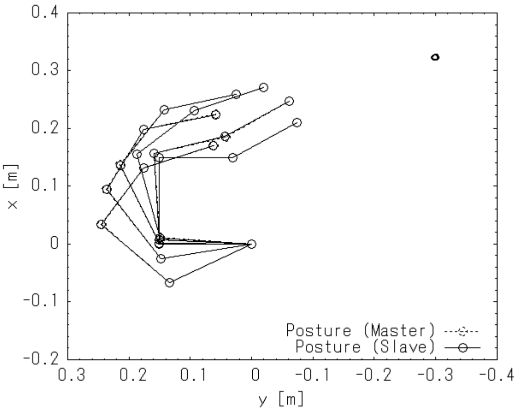

Fig. 15. Configuration Response ($0 < t < 2.5$)

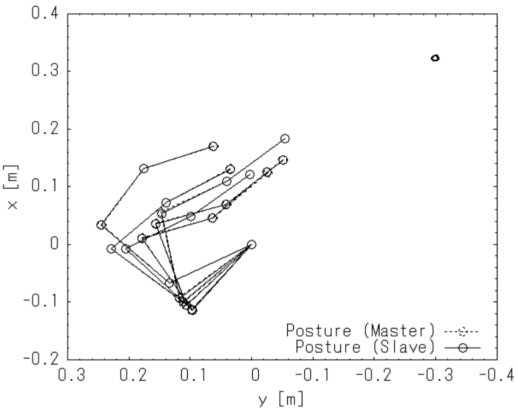

Fig. 16. Configuration Response ($2.5 < t < 5$)

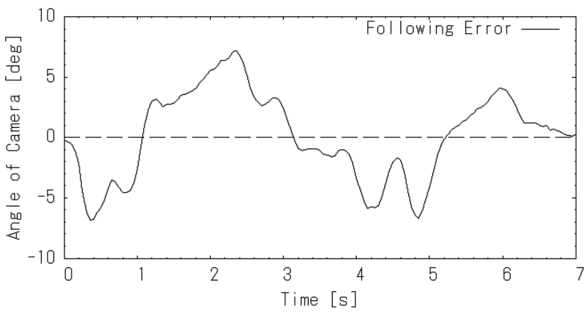

Fig. 17. Tracking Error Angle α

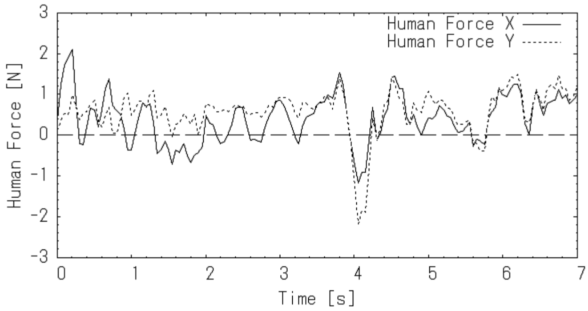

Fig. 18. Estimated Human Force

part, visual feedback controller is constructed to track the target object consequently. The validity of the proposed approach is verified by several numerical and experimental results.

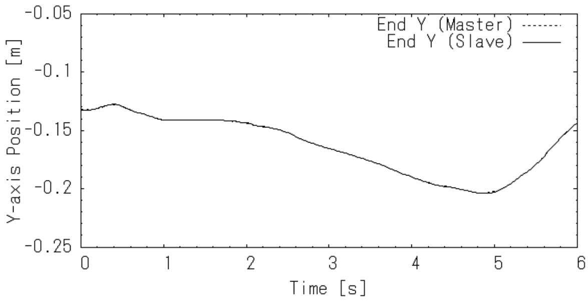

Fig. 19. Tip Position Responses (y)

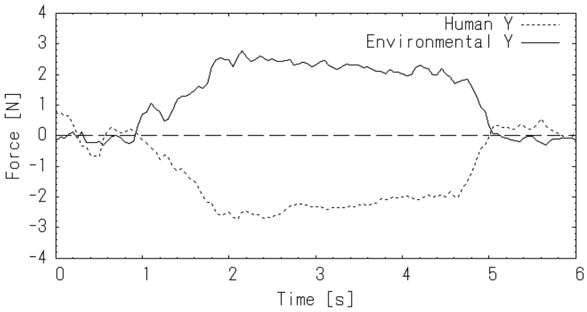

Fig. 20. Tip Force Responses (y)

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